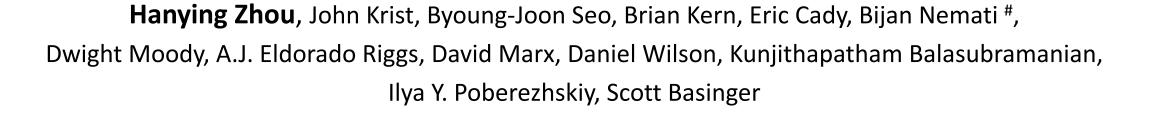


# WFIRST Phase B HLC Occulter Mask Baselining And Testbed Performance Validation



Jet Propulsion Laboratory, California Institute of Technology

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## **CGI HLC Modeling: From Design to Testbed Demo**



WFIRST-CGI Phase B PDR (in Sept): nFOV/HLC Band 1 testbed demo\*

Purpose: Meet the raw contrast requirement within required time allocation,

both on ground and in-orbit WFC

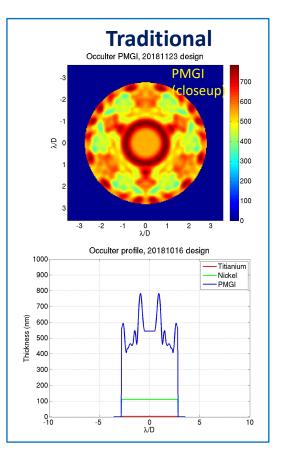
- Modeling actively involved:
  - Mask design: mask baselining
     Fabrication error tolerancing, flight performance prediction, general feedback to design
  - Testbed demo: performance validation
     Ground WFC (from flat DM)
     In-orbit WFC (from ground seed DM)
     Open loop sensitivity
  - Testbed WFC diagnosis
     Ground WFC, when from design DM solution

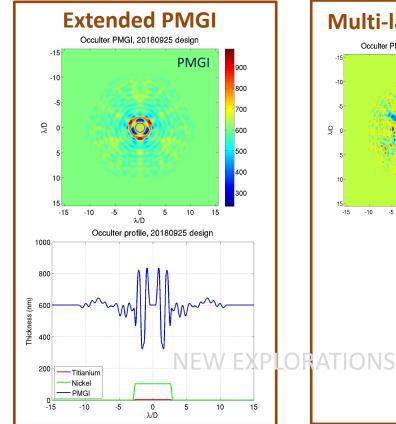
<sup>\*</sup> Seo, J. et al. Proc. SPIE 11117-53, this conference Proc. (talk on Thursday)

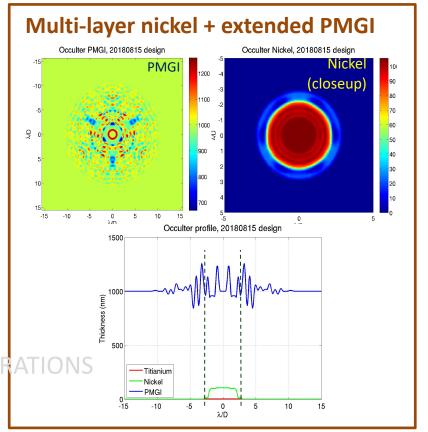
# Exploratory HLC Occulter Mask Designs for Phase B



- Promising performances; but requires new fabrication process / method
  - Q: Are they viable? Are there risks?
- Modeling to address design mask viability concern:
  - Robust to fabrication, I&T, and launch uncertainties? Impact on LOWFS? Meet key L-3/4 Reg's?



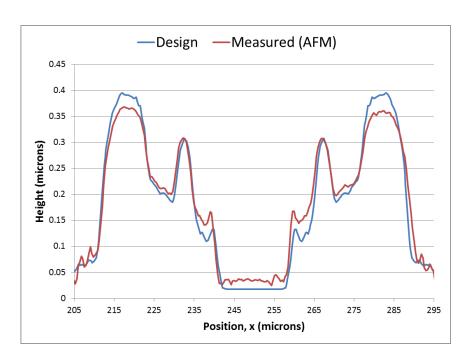




### Major Fab Errors: Measurement and In Model

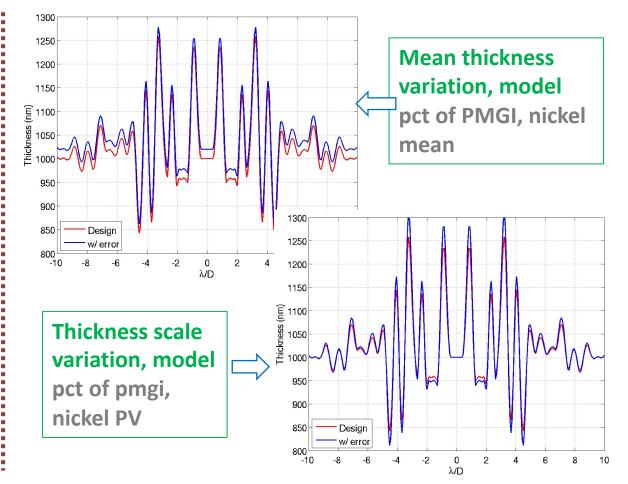


- For modeling: derive HLC occulter transmission from thin-film equation directly
  - "Design" mask typically given in complex transmission (for modeling)
  - Add thickness errors for both PMGI and nickel in terms of mean offsets and scale variations



20~30% at some peak/valley locations\*

\* Dan Wilson (2014)





## Main Findings From Exploratory Design Evaluation



- Extended PMGI and/or multi-nickel designs require tighter fabrication tolerancing
  - 1~ 5% for PMGI mean, scale, Nickel mean and scale, exceeding existing fabrication capabilities
  - More work needed in better design optimization (to reduce fab risk)
- **Traditional style designs: possible** options that can meet Phase B telescope interface Req.

Band	Design	NI (full DH)	thruput @ 6I/D	DM strokes	Z2 3-4I/D	Z4 3-4I/D	Z6 3-4I/D	Nickel mean	Nickel scale	PMGI mean	PMGI scale	Note
				Rms/PV	1nm	1nm	1nm	10%	10%	10%	10%	
Band 1	1	4.41E-09	3.13%	37/255; 40/293	1.10E-09	9.40E-09	4.80E-09	7.70E-08	1.10E-06	7.20E-09	5.60E-09	Multi nickel
	2	3.45E-09	4.09%	31/223; 33/215	5.10E-10	1.88E-08	6.50E-09	1.07E-08	1.54E-08	2.76E-08	1.17E-09	Multi nickel
	3	1.94E-09	3.36%	39/267; 40/241	2.29E-10	3.92E-09	7.36E-10	6.00E-10	NA /	2.35E-08	4.89E-09	Ext'd pmgi
	4	2.40E-09	4.70%	29/211; 30/204	2.45E-10	1.46E-08	2.67E-09	6.11E-10	NA	2.52E-08	7.50E-10	Ext'd pmgi
	5	2.03E-09	4.57%	29/211; 30/204	1.27E-10	8.69E-09	2.81E-09	3.67E-10	NA	1.02E-08	3.75E-10	Ext'd pmgi
	6	1.92E-09	4.10%	30/225; 35/226	1.05E-10	5.81E-09	1.82E-09	8.16E-11	NA	7.20E-11	4.91E-12	Traditional
	7	1.73E-09	4.56%	27/185; 32/204	9.55E-11	5.42E-09	1.69E-09	8.72E-11	NA	3.78E-10	1.06E-11	Traditional
	8	1.90E-09	4.10%	31/274, 34/276	1.52E-10	6.53E-09	2.39E-09	6.05E-11	NA	5.90E-10	1.34E-10	Traditional
Band 3	9	5.25E-09	5.33%	33/212; 34/213	1.27E-10	8.69E-09	2.81E-09	5.48E-09	7.24E-09/	4.80E-09	4.04E-09	Multi nickel
	10	4.39E-09	4.85%	37/259; 39/230	6.46E-11	1.18E-08	2.26E-09	9.80E-10	2.70E-09	2.90E-09	2.00E-09	Multi nickel
	11	5.41E-09	3.95%	27/185; 32/204	1.64E-10	3.45E-09	1.30E-09	5.36E-11	NA	5.73E-10	3.27E-11	Traditional

**Multi-layer nickel** + extended PMGI

**Extended PMGI** 

**Traditional** 

**Multi-layer nickel** + extended PMGI

**Traditional** 

## Standard Procedure For Baselining Design Mask



Many **inconsistencies and errors** among designs found during preliminary design evaluation:



**Standard procedure** for systematic evaluation and mask baselining:

Model, Aber and error inputs, WFC scheme/flight constraints, evaluation metric, etc.

**Model** = Full PROPER *Contrast Truth* sub-model + Compact *Control* sub-model

Fresnel propagation, distr. aber

FFT propagation except btwn DM1 <--> DM2

- Full flight CBE optic surf aber (tel +toma +CGI)
- Ground-to-orbit OTA-CGI misalignments
- Polarization effect
- FPM fab errors (PMGI &Nickel, mean & scale)

Compressed aberration from full model; "known" imperfections only

For high fidelity

For flight-like WFC





## Standard Procedure For Baselining Design Mask

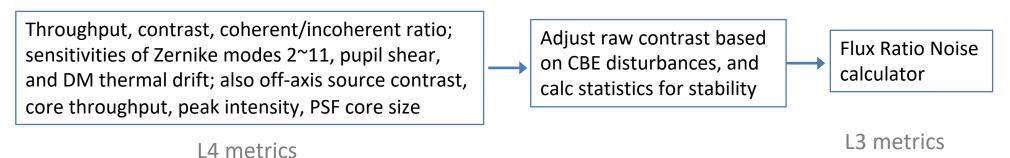


### **Standard procedure** for systematic evaluation and mask baselining:

Model, Aber and error inputs, WFC scheme/flight constraints, evaluation metric, etc.



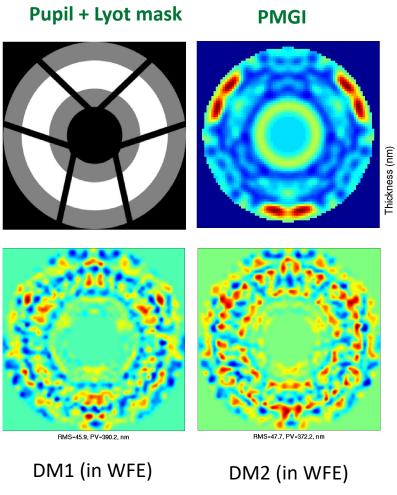
- Low order WFE flattening before EFC
- 3 subbands ctrl; weighted E field averaging for each subband E field
- DM neighbor rule and maximum voltage constraints
- **Evaluation Metric**: Flux Ratio Noise (L3), based on selected key L4 metrics:



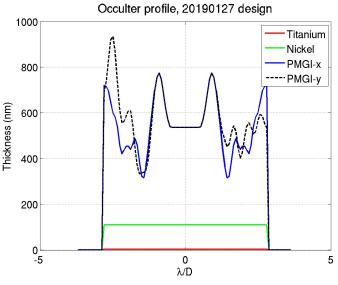
## Phase B HLC/nFOV Band 1 Baseline Design







#### PMGI, Nickel, Titanium profiles scan



- Traditional style design
- But asymmetrical PMGI

### L-3/4 performances:

3.4% Throughput: Static init raw C: 2.7e-9 Photometry N: 1.4e-9 C stability: 0.6e-9

FRN: 1.4e-9\*

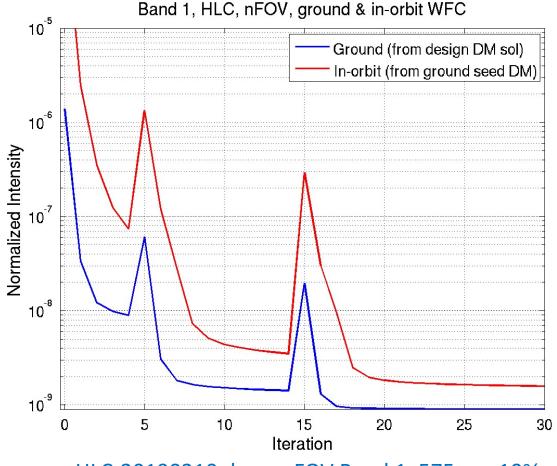
<sup>\*71%</sup> margin, slightly > SRR design

## Flight WFC Prediction: Ground & In-Orbit WFC

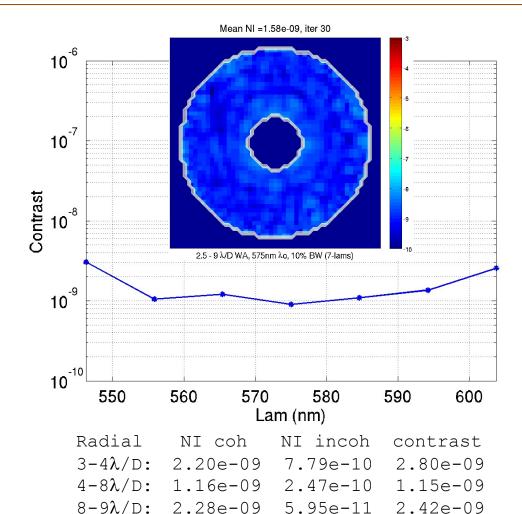


Can dig a dark hole that meets L4 Req, within required time allocation\*, for both on ground and in-orbit

\* Equivalent to max 30 iterations







1.53e-09

2.48e-10

1.51e-09

Mean:

### **Testbed WFC Modeling:** Band 1 HLC/nFOV - Overview



Model validation for both ground & simulated in-orbit WFC, Tech testbed configuration

**Model:** compact for both contrast truth & control (mostly FFT based except DM1 <--> DM2)

- Chromatic pupil E fields, flat DM, DM gains; all TTB PR measurement
- Occulter fabrication errors\*: PMGI mean & scale, nickel mean; AFM measurement
- Pupil mask and Lyot mask clockings (relative to FPM & camera view); testbed characterization
- DM misalignment: tilts and lateral shifts; testbed characterization (past)
- ☐ For in-orbit WFC: all above, plus OTA-s WFE, pupil mask clocking, pupil mask shear, CGI internal misalignment, and DM hysteresis (ground DM seed strength)\*

TTB Meas. based input

\* As knowledge errors; the rest are as known/alignment errors

#### WFC:

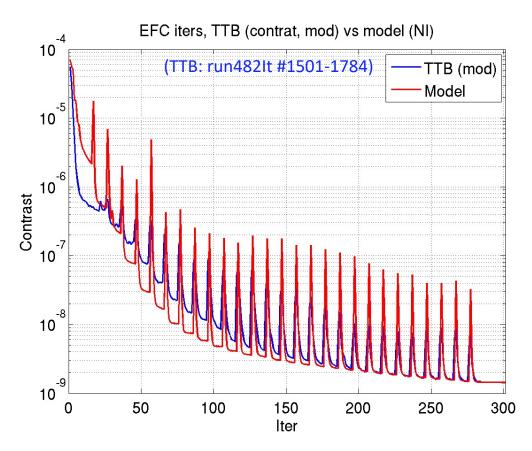
- For Ground EFC: start from flat DM solution
  - Frequent Jacobians update & beta kick cycles (alternate hi/lo regularizations); no limitation on # of iters
- For in-orbit EFC: start from ground seed, add flight flat, and subtract out ground flat
  - Single Jacobian, 1 or 2 beta kick cycles (or quick early multi beta cycles), max 30 iters
- 3 subbands ctrl; weighted E fields averaging for each subband E field; 7 lambdas contrast scoring
- DM neighbor rule and max voltage constraints

### Model / TTB Comparison, Ground WFC, From Flat

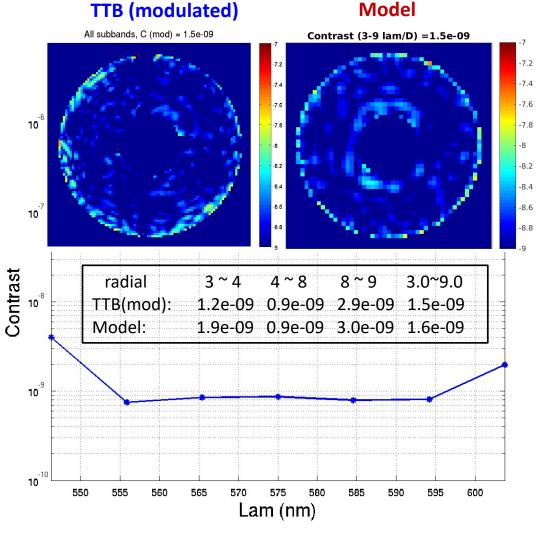


### Model validates TTB ground WFC performance:

- Both meet raw contrast requirement
- Agrees well in contrast floor and convergence speed



#### Final dark hole raw contrast



### Model/TTB Comparison, In-Orbit WFC, From Ground Seed

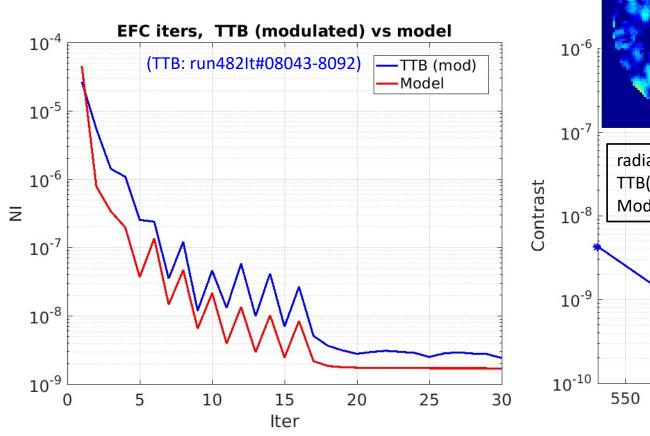


#### Model validates TTB simulated in-orbit WFC:

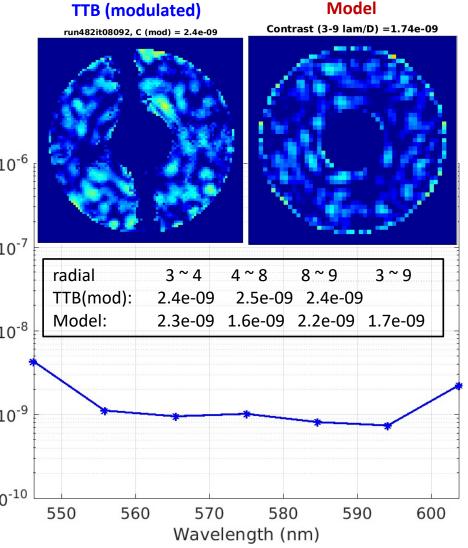
• Both meet raw contrast requirement

\*modulated part

- W/n the required time allocation (# of iterations)
- Agrees well in contrast floor & convergence rate



#### Final dark hole contrast



### Model/TTB Agreement, Open Loop Sensitivities

10<sup>-5</sup>

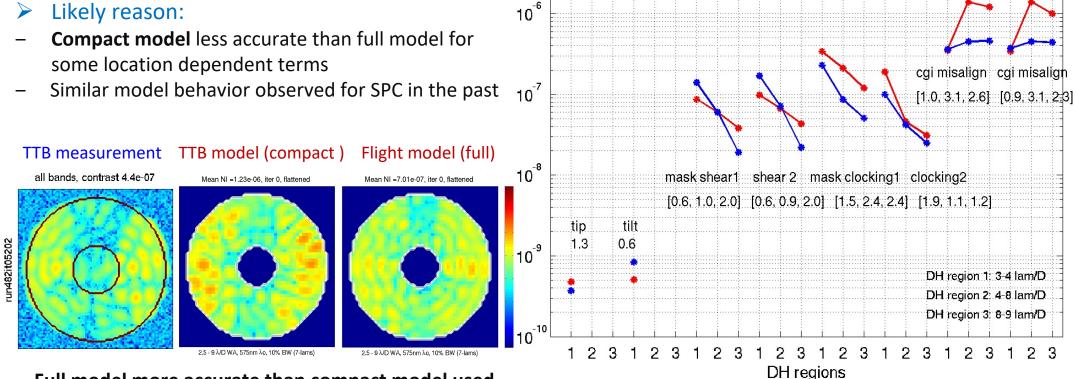
Model TTB



Open loop sensitivities, model vs TTB

- Generally good match (< factor of 2) except
  - ~3X diff in CGI internal misalignment\*: \*Src offset at FSM, compensated by FPM

#### Likely reason:



Full model more accurate than compact model used



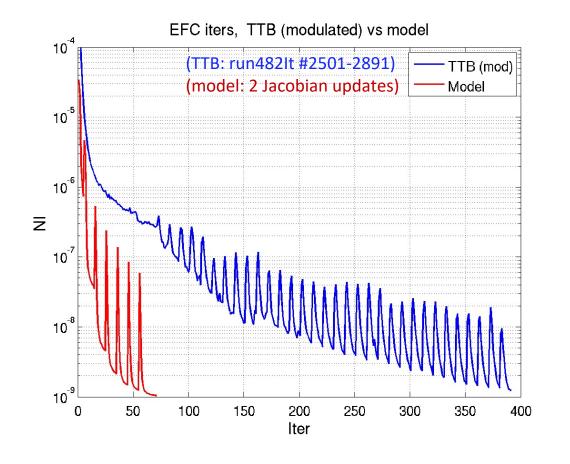
#### 08/12/2019

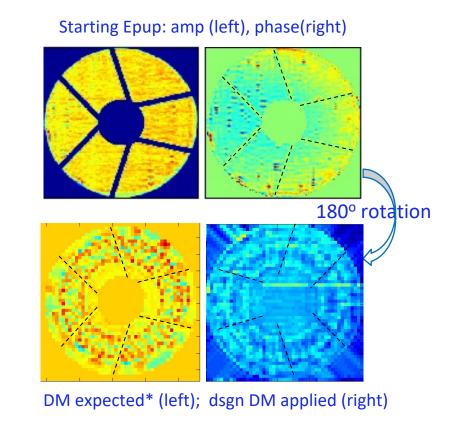
### TTB WFC Diagnosis, Ground WFC, From Design DM



Historically, testbed WFC disagrees w/ model prediction when starting from design DM solution

Reason identified: incorrect application of design DM solution on TTB
 Once corrected → much shortened and less Jacobian-update-need ground WFC





<sup>\*</sup> Diff btwn start/ end EFC DM, when starting from flat DM

### Summary



#### **HLC** occulter mask evaluation

- Identified potential risks w/ early exploratory mask designs and fabrication process As a result, traditional style design chosen for risk aversion
- Developed standard evaluation procedure, for masks design evaluation / optimization\*, flight performance prediction

### Testbed WFC performance validating

- Confirmed current Phase B design can meet raw contrast req. w/n the time allocation
- Agreed well in:
  - Ground WFC: convergence speed, raw contrast floor, etc.
  - In-orbit WFC: convergence speed, raw contrast floor, etc.
  - Open loop sensitivity: tip/tilt, pupil mask clocking/shear, CGI internal misalignment
- Identified implementation error on testbed
  - Ground WFC, when starting w/ design DM solution
- Closed major gaps btwn model predictions and testbed results, improved model fidelity

<sup>\*</sup> AJ, Riggs, A simplified version is now in design pipeline



### **BACKUPS**



### Flight WFC Modeling: All Bands (1,3,4) - Overview -1



**Number of Jacobian (and iteration)** of in-orbit WFC, *flight optics and configuration* 

**Model** = [full PROPER *contrast truth* sub model + compact *control* sub model]:

#### **Contrast truth, for ground:**

- Flight CGI part optic surface aberrations (i.e., excluding front end telescope and toma optic up to FSM); no polarization; but add 20nm rms WEF for ground OTA-s, as known error
- FPM fabrication error for HLC: PMGI mean offset and scale, nickel mean, as knowledge error

#### **Contrast truth, for In-orbit:**

- Full flight optic surface aber (telescope + toma +CGI), and polarization effect, consistent with flight CBE, as known error
- FPM: same fabrication error for HLC: PMGI mean, PMGI scale, nickel mean, as knowledge error
- OTA: lateral misalignment, clocking, magnification, all as known error
- CGI: internal misalignment (misalign DM2 from DM1), as known error
- DM: hysteresis, uniform difference in starting actuator height, as knowledge error

#### **Compact control**:

Include known errors as derived from full model but not knowledge errors



## Flight WFC Modeling: All Bands (1,3,4) – Overview -2



Number of Jacobian (and iteration) of in-orbit WFC, flight optics and configuration

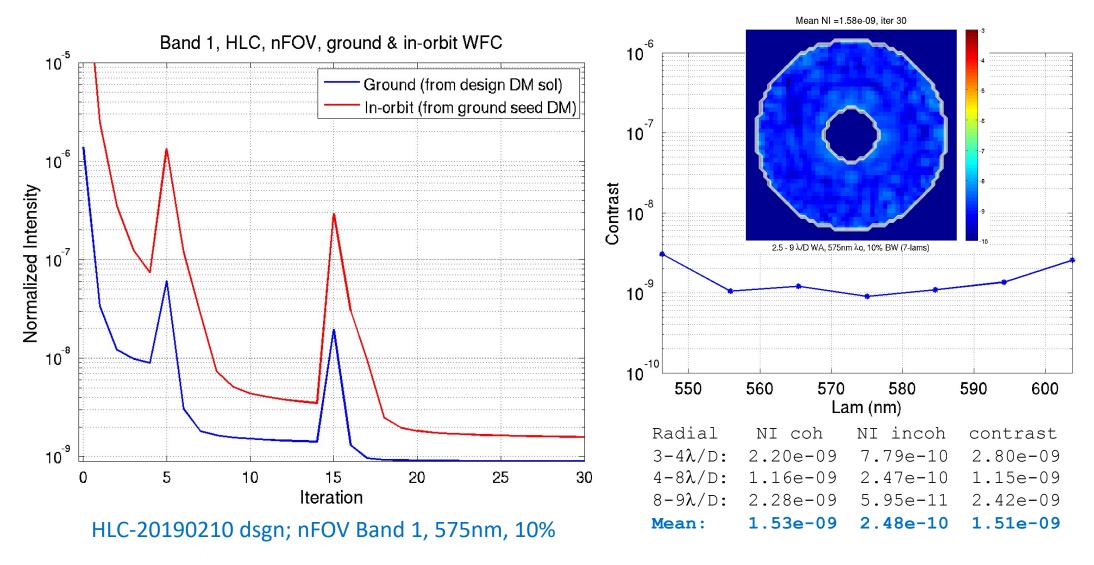
#### • WFC

- Low order WFE flattening (split between two DMs) before EFC
- EFC: 3 subbands ctrl for nFOV & wFOV; 5 for IFS;
  - For ground WFC: start with design setting (e.g., use design DM pattern for nFOV mode)
    - No limitation on frequency of Jacobian update or number of iterations
  - o For In-orbit WFC: start with ground seed; but subtract out ground WFE
    - Single Jacobian calculation,
    - Max 30 iterations; max 2 cycles of beta kicks
- Probing (sensing) is substituted by weighted averaging of E fields for each subband E field
- DM neighbor rule and max constraints
- Contrast scoring: 7 lambdas for Bands 1 & 4 (nFOV & wFOV); 11 lambdas for Band 3 (spectroscopy)

### Band 1, HLC/nFOV, Ground and In-Orbit WFC



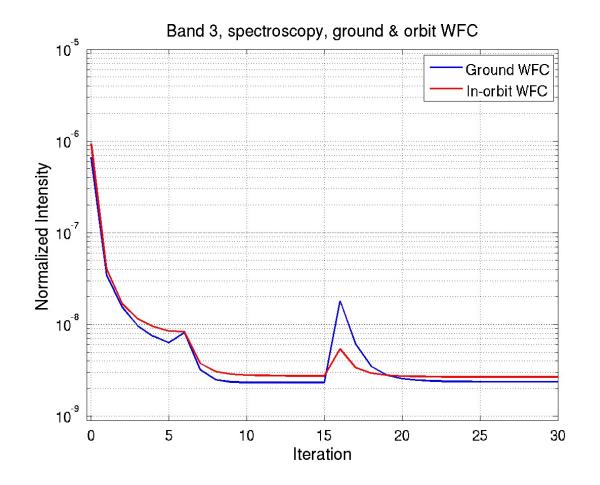
Can reach dark hole that meets L4 Req, w/ single Jacobian, max 30 iter, for both on ground and in-orbit



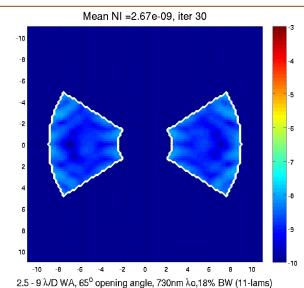
### Band 3, SPC/Spectro, Ground and In-orbit WFC



#### Can reach dark hole that meets L4 Req, w/ single Jacobian, max 30 iter, for both on ground and in-orbit



IFS-20190130 dsgn; Band 3, 730nm, 18%

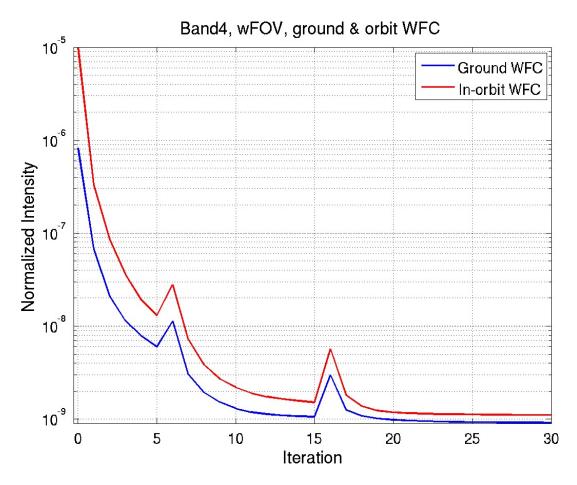


NI coh NI incoh contrast 3.52e-09 2.59e-09 1.45e-09 1.82e-09 1.05e-09 2.12e-09 1.38e-09 5.55e-10 1.56e-09 1.06e-09 3.08e-10 1.19e-09 2.03e-09 3.60e-10 2.30e-09 7.66e-09 4.19e-09 2.10e-10 1.57e-09 5.18e-10 1.77e-09 3.06e-09 2.09e-09 6.56e-10

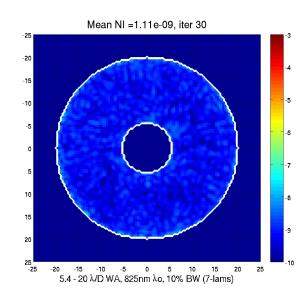
### Band4, SPC/wFOV, Ground and In-orbit WFC



Can reach dark hole that meets L4 Req, w/ single Jacobian, max 30 iter, for both on ground and in-orbit



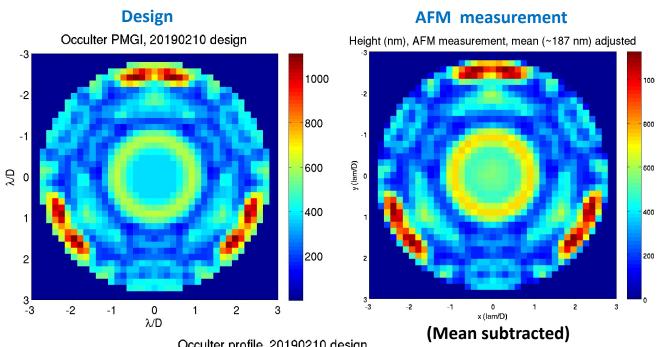
wFOV -20181220 dsgn; Band 4, 825nm, 10%



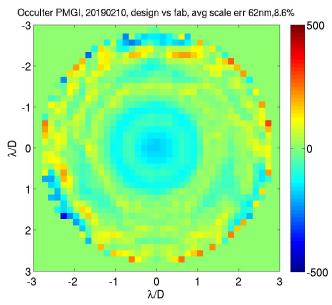
1.48e-09	4.38e-11	2.44e-09
1.03e-09	1.57e-11	1.09e-09
2.93e-09	3.71e-11	5.09e-09
7.95e-10	9.97e-12	8.33e-10
1.16e-09	8.42e-11	1.40e-09
NI coh	NI incoh	contrast

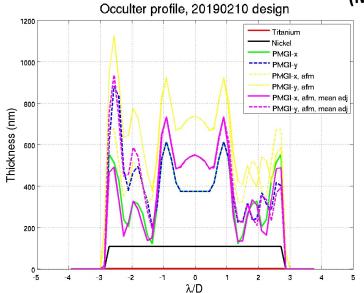
### Misc. Info: Occulter Mask Fab Error





### Difference (mean subtracted)





#### Based on AFM measurement

Mean PMGI offset: ~ 187nm

Avg PMGI scale err: ~ 9%

w/n conservative estimates

Minor impact on WFC NI / iter